The potential for carbon sequestration in grass seed cropping systems in western Oregon: the state of the science as reported in the literature as of December, 2006

by Danya Rumore[1], Elizabeth Sulzman[2], and William Young[2]

[1]Undergraduate student in Environmental Sciences, Oregon State University, Corvallis, OR
[2]Dept. of Crop and Soil Science, Oregon State University, Corvallis, OR

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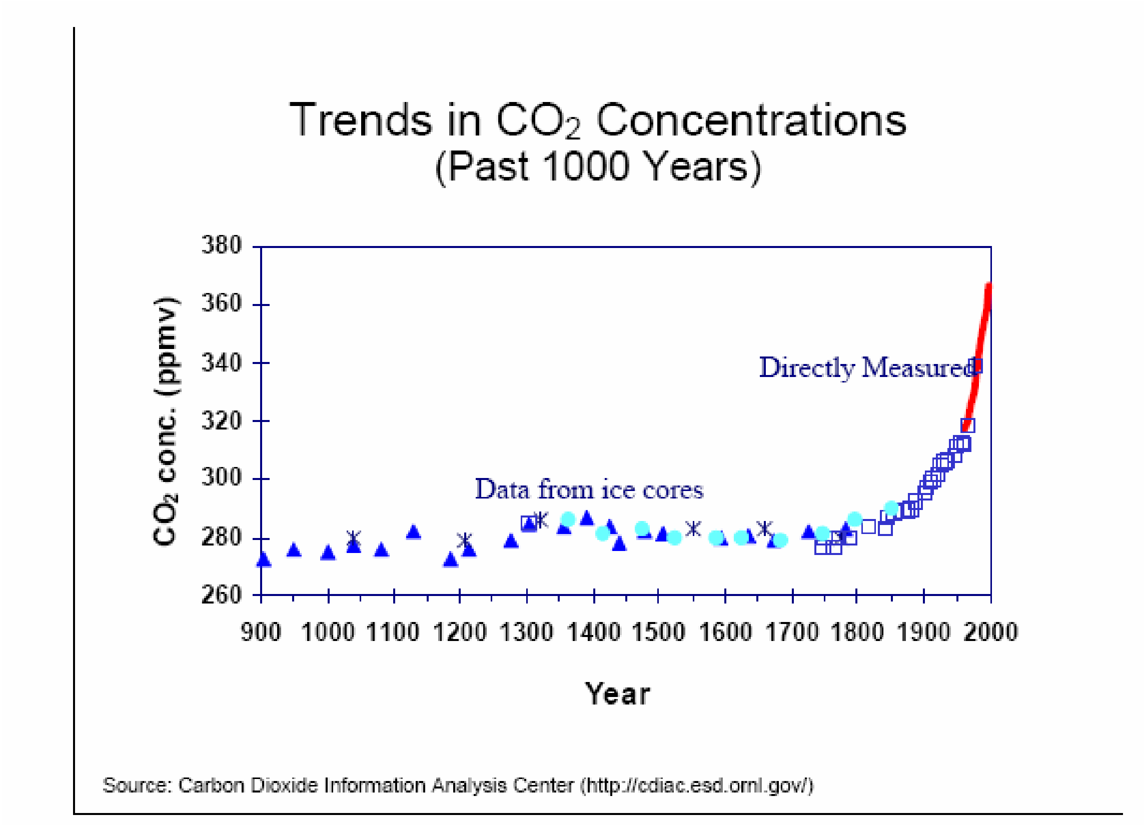
Introduction:

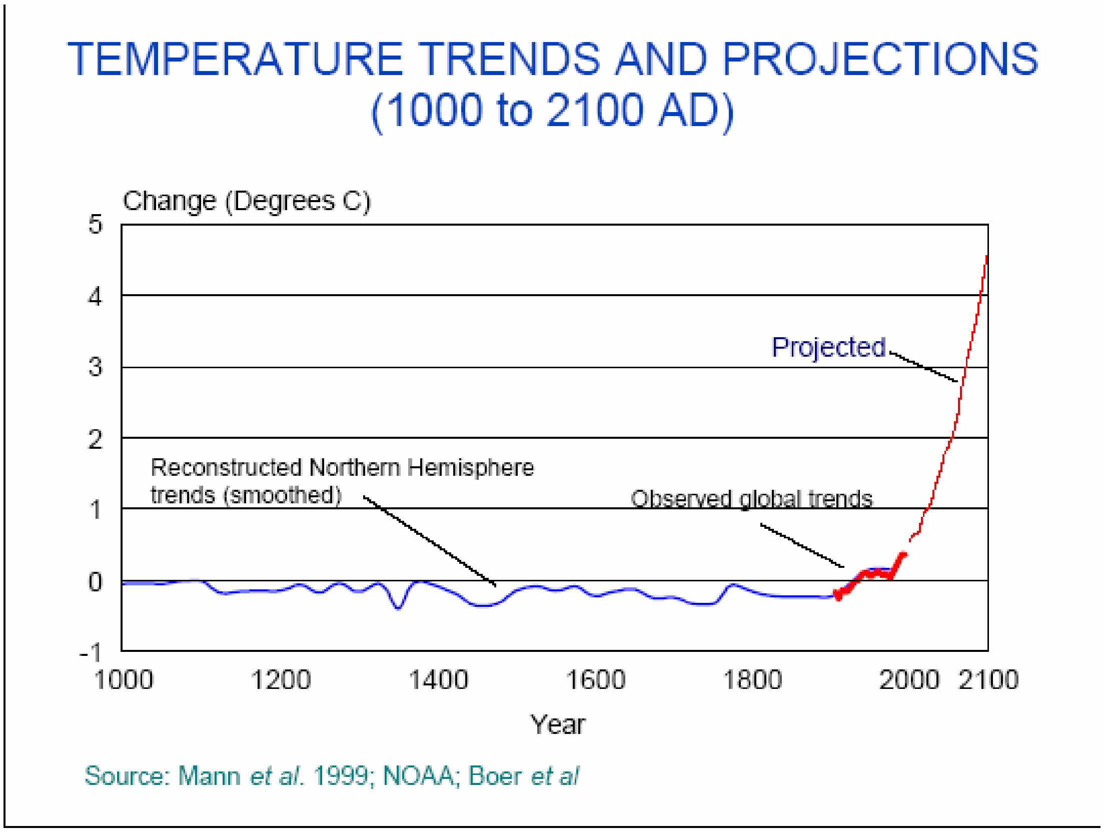
Emissions of fossil-fuel derived CO_2 has increased dramatically since the beginning of the Industrial Revolution (Bird et al. 1996). Due to increased fossil emissions as well as land-use related releases of CO_2, atmospheric concentrations of CO_2 have risen from 280 ppmv in 1750 to 380 ppmv in 2005 (Figure 1; National Oceanic and Atmospheric Administration (NOAA)). Today's CO_2 concentrations are now higher than any seen in at least the past 650,000 years (NOAA).

Figure 1.



Carbon dioxide (CO_2) is a greenhouse gas (GHG) linked with global warming. The increase in global temperatures due to radiative forcing by CO_2 and other GHGs in the atmosphere has been estimated at 1.1°F during the 20th century, and is predicted to be 2.5-10.4°F by 2100 relative to 1990 (Figure 2; Intergovernmental Panel on Climate Change (IPCC) 2001). Analyses of ice cores and other paleoclimatic data suggest this rate of increase is faster than any experienced during the last 10,000 years (IPCC 2001). Although the implications of global warming and the exact location of the impacts remain uncertain, it is likely that warmer temperatures will change the amount, distribution, and intensity of precipitation, growing season duration, biogeography, and soil biological, chemical, and physical characteristics throughout the world. For this reason, elevated concentrations of greenhouse gases in the atmosphere are of great concern.

Figure 2.



http://www.msc-smc.ec.gc.ca/saib/climate/Climatechange/CC_presentation_e.PDF
see also: http://www.ncdc.noaa.gov/oa/climate/research/trends.html

In order to assess the potential implications of radiative forcing and the greenhouse effect, sources and sinks for CO_2 need to be identified and quantified and the mechanisms driving the CO_2 fluxes into and out of these pools must be better understood. Historically, there have been large losses of carbon from soils as a result of land use. For example, conversion of forest to pasture often results in a large pulse of carbon to the atmosphere. Houghton et al. (1999)

estimated that land clearing in the USA released nearly 33 billion tons C to the atmosphere before 1945, and that subsequent reforestation has resulted in an uptake of about 2 billion tons C. Similarly, historical changes in land use for agricultural purposes have shifted the natural balance of carbon between soil and the atmosphere. Estimates of soil organic carbon (SOC) loss due to conversion of natural to managed ecosystems range from 44 to 582 billion tons of carbon (C), with recent estimates centering on roughly 88 billlion tons C (Lal 2003).

Current research shows that adoption of certain land management practices can promote SOC storage, and may allow agricultural lands to be converted back into carbon reservoirs (e.g., Cole et al. 1996). Optimizing agricultural management for accumulation of soil organic carbon can result in sequestration of atmospheric CO_2, perhaps thereby partially mitigating the increase in atmospheric GHGs (West and Post 2002). This paper analyzes existing literature concerning the carbon sequestration potential of grassland and pasture systems and the impact of no-till and conservation tillage practices on soil SOC storage in an attempt to better quantify the potential for Oregon grass seed producers to participate in carbon credit trading.

Background -- Carbon Cycle and Carbon Sequestration Basics:

Carbon (C) moves among four major reservoirs: the oceans, the atmosphere, the geosphere, and the terrestrial biosphere (soils plus vegetation). Oceans are the largest global C pool, storing an estimated 42 trillion tons C, followed by the geologic pool of 5.5 trillion tons C, the soil organic pool of 1.7 trillion tons C (with another 0.6 trillion tons stored in terrestrial vegetation), and the atmospheric pool of 0.8 trillion tons (Lal 2003). The geologic pool interacts with the atmosphere through volcanism and fossil fuel burning. Much of the oceanic C pool is "inert" on timescales shorter than millennia. Much less is known about carbon cycling in soil than in any of the other main carbon reservoirs (Schlesinger et al. 1999).

Carbon flows between soil and the atmosphere through the paired processes of photosynthesis and respiration. Photosynthesis is the process by which plants fix CO_2 from the atmosphere into carbohydrates, which can then be converted to plant structural components or other necessary compounds. These carbon compounds enter the soil when plants die or shed litter, or through the process of root exudation. Upon entering the soil the carbon is primarily stored as soil organic matter (SOM). A large portion of recently deposited crop residues break down rapidly via microbial respiration, thereby releasing CO_2 into the atmosphere (Schlesinger

1999). Some carbon is not broken down, or is only partially degraded, and then converted to new C compounds by soil microorganisms. This carbon can become either physically or chemically stabilized, or made resistant to further decay, thereby sequestering carbon from the atmosphere in the form of soil organic carbon. A key point to note is that the amount of carbon sequestered in soils is linked to the amount of nitrogen available in the system (either naturally, or through fertilizer application). This is because SOM has a fairly constant C:N ratio of 10-20 (Brady and Weil 2002). Thus, for each ton of C sequestered, 100-200 lbs of N must be available.

Carbon Sequestration in Soils of Grassland and Cropping Systems:

Grassland soils store relatively large amounts of SOC due to their fertility and lack of disturbance. Grasslands occupy roughly 3.1 billion acres of the world's land surface, and thus may have a large potential to affect the amount of carbon in the atmosphere (IPCC 2001). Globally, grassland soils store an estimated 194 billion tons C, or roughly 8% of the world's soil carbon (IPCC 2001). This estimate is likely biased high, however, as it implies 5% organic matter content in surface soils, which is unlikely in arid land soils (Steve Petrie, pers. comm.). Further, the potential for native grasslands to fix additional C is limited unless rainfall, soil temperature, or N inputs increase (Steve Petrie, pers. comm.). Below we present data from several different grassland and cropping systems under a variety of management regimes, in an attempt to identify a reasonable range of C sequestration that might be expected by grass seed producers in Oregon.

Conservation Reserve Program:

Many of the studies analyzing soil carbon sequestration in grasslands have been geared toward Conservation Reserve Program (CRP) land. The CRP is a federal agricultural land retirement program administered by the USDA Natural Resources Conservation Service with the intent of removing highly erodible and environmentally sensitive land from production. CRP land must be planted with vegetative cover (often native grass) and cannot be cropped for 10 years. CRP management helps to restore soil biological, physical, and chemical properties, provides wildlife habitat, and may be instrumental in increasing the ability of soil to sequester carbon.

Carbon sequestration rates and values reported for CRP land vary, but the potential for sequestration on CRP land is often limited by low to intermediate rainfall and a prior history of erosion (Steve Petrie, pers. comm.). Follett et al. (2001) reported C sequestration under CRP in areas of summer rainfall to be between 0.27 to 0.45 tons C $acre^{-1}$ yr^{-1}. In a study of CRP lands in Texas, Kansas and Nebraska, Gebhart et al. (1994) found that SOC may accumulate at an average rate of 0.49 tons C $acre^{-1}$ yr^{-1} in the surface 118 inches. Comparable studies found lower rates in less productive grass systems. Robles and Burke (1998) did not find any significant soil carbon gains in CRP land soil within 6 years of cultivation in a semiarid grassland, but it is possible that over a much longer period of time some amount of sequestration would occur even in low fertility soils. Research by Bronson et al. (2004) in the Southern High Plains found that total carbon and nitrogen content in CRP land was greater than that of nearby cropland soils in the 0-2 inch layer. Total C for CRP soil in the 0-2 inch layer was 2.4 ± 0.2 tons $acre^{-1}$ versus 1.5 ± 0.2 tons $acre^{-1}$ for irrigated cotton soil (Bronson et al. 2004). Below 2 inches, their study found no statistically significant differences between CRP and cropland soil SOC values. However, they did report noticeably higher C storage in native rangeland (NR) soil than in cropland or CRP for all depths (Bronson et al. 2004). Similarly, Huggins et al. (1997) reported that after 7 years in the CRP, soil C and N in a loamy soil was still less than that of a tall grass native prairie with the same soil, and Potter et al. (1999) reported that soil C and N on a 60-year restored grassland on a clay soil were still less than native prairie values.

These CRP studies show that productivity (often a function of soil moisture) is a main factor in increasing soil C sequestration capacity of grassland systems. They also indicate that native rangeland and prairies sequester greater amounts of carbon than do CRP and restored grassland systems. The Idaho Soil Conservation Commission (2003) suggests that the use of CRP land to sequester carbon is limited. Their analysis was based on data from Idaho, but may be relevant to similar climatic regions of the greater Pacific Northwest.

Conversion of Cropland to Grassland:

The IPCC has rated conversion of marginal agricultural land to grassland, forest, or wetland as having a medium potential for global CO_2 mitigation (compared to the high potential of reduction in deforestation and the low potential of use of agroforestry) (IPCC 1996). Conversion of cropped land to perennial grassland tends to increase SOC storage due to increased SOM formation (a result of high root C production), improved aggregation, and better soil structure due to lack of soil disturbance. Restoration of degraded soils to grassland also reduces erosion-induced emissions of CO_2 and may restore depleted SOC pools (Lal 2003).

Although research consistently shows increases in SOC sequestration due to conversion of cropland to grassland, estimated sequestration rates and total SOC values range widely, perhaps in part because of the availability of N. (As mentioned above, for any C sequestration, there must be a readily available source of N.) Gebhart et al. (1995) documented mean soil accumulation rates of 0.07-0.54 tons C acre^{-1} yr^{-1} due to conversion of USA cropland to grassland seeded for set-aside programs. At the upper end this would require about 110 lbs N per acre per year. For the UK, Tyson et al. (1990) reported a mean soil C accumulation rate of 0.33 tons C acre^{-1} yr^{-1} as a result of conversion of agricultural land to planted grassland. In New Zealand, Haynes et al. (1991) recorded a mean soil C accumulation rate of 0.45 tons C acre^{-1} yr^{-1}. In a study of soil carbon changes in cultivated land converted to grasses in east-central Saskatchewan, Mensah et al. (2003) estimated a net C gain of 0.3-0.4 tons C acre^{-1} yr^{-1} in the surface six inches of soil. Their study reported concentrations of 26.5 ± 1.8 tons C acre^{-1} for the restoration treatments compared to 23.5 ± 1.2 tons C acre^{-1} for the cultivated treatment. In eastern Oregon, Machado et al. (2006) found that after 73 years, grassland pasture with no tillage and large amounts of grass residue had higher SOC content than conventionally-tilled winter wheat systems, with 36.4 tons C acre^{-1} in grass pasture versus 22.5 tons C acre^{-1} for conventional tillage winter wheat *(Tricicum aestivum)* fallow systems and 33.4 tons C acre^{-1} for fertilized conventional tillage continuous crop winter wheat systems. Variable amounts are in part due to variations in sampled depth of soil and variable time periods over which measurements were taken. In general, perennial grassland systems with minimal disturbance and high vegetative root mass sequester the greatest amounts of carbon.

Conservation tillage and no-till agricultural systems:

Probably the most often cited method for sequestering carbon in agricultural soils is the use of conservation (reduced) tillage, or “no-till” (NT) management. No-till agriculture greatly reduces the amount of soil disturbance typically associated with conventional agriculture. Reduced tillage slows decomposition of SOM and can stabilize carbon in microaggregate soil structures, leading to increased soil C. Sperow et al. (2003) found the soil C gain from use of NT in the eastern Corn Belt to be 0.09-0.27 tons C $acre^{-1}$ yr^{-1}. Beare et al. (1994) found that total C accumulations on kaolinitic soils of Georgia after 13 years under no-till management were 18% higher than conventional systems. In a study of cropping system effects on carbon sequestration in a 17 inch precipitation zone of eastern Oregon, Machado et al. (2006) found that tillage influenced the amount and distribution of SOC in the soil profile. Their results indicated that relative to 1931 levels, conventional tillage (CT) reduced SOC in all layers of soil except the 4-8 inch zone, where plowing deposits crop residue. In the NT system studied by Machado et al. (2006), SOC concentrations closely mirrored a grass pasture system, with the highest SOC in the 0-4 inch layer, and decreasing SOC with soil depth. The authors concluded that SOC content is highest in grass pasture, but that potential to sequester SOC increases with reduced tillage and more intensive cropping. Their study also found that after only 6 years of conversion to NT, lack of tillage was beginning to reverse the effects of 73 years of CT wheat fallow cropping on SOC accumulations (Machado et al. 2006). West and Post (2002) compiled data from 67 long-term agricultural experiments from around the world and concluded that conversion from CT to NT can sequester, on average, 0.25 ± 0.06 tons C $acre^{-1}$ y^{-1}. Given their reported lifetime of 15-20 years until a new equilibrium is reached, this amounts to 5 tons C per acre. In contrast, using an inventory approach for U.S cropland soil, Sperow et al. (2003) estimated that the adoption of NT on all currently annually cropped U.S land (319 million acres) would increase soil C sequestration by 52 million tons yr^{-1}. They conclude that this level of agricultural soil C sequestration “could play a meaningful, but not predominant, role in helping mitigate GHG increases.” For comparison, estimated CO_2 emissions from agricultural production in 1998 were 47 million tons C (Sperow et al. 2003).

Carbon sequestration through better management of existing grasslands

Conant et al. (2001), in a review of 115 studies on soil C in grasslands of the world, highlighted several practices shown to increase C storage in grassland soils, starting with conversion of previously cultivated land back to grassland, and including sowing of legumes, introduction of earthworms, improved grazing management, and improved irrigation and fertilizer management (Table 1). Note, however, that Schlesinger (1999) argues that fertilization amounts to a net addition of C to the atmosphere, because of the amount of fossil C released during the manufacture of synthetic fertilizers. Nevertheless, the synthesis compiled by Conant et al. (2001) suggests that between 0.05 to 1.36 tons C $acre^{-1}$ y^{-1} can be sequestered in surface soils during the first 40 years following improved management practices.

Lal (2003) also compiled a number of studies specifically addressing improved management practices. Lal's compilation indicates that manuring or fertilization can lead to sequestration of 0.03 to 2.01 tons C $acre^{-1}$ yr^{-1} (Table 1). Note that manuring and fertilization were not treated separately, and the overall impact of fertilizers on the C budget has been questioned by Schlesinger (1999). The wide range of values he reported may in part be due to lumping of the two fertilization methods, or to the fact that he cited studies over a very wide geographical area (including Australia, Austria, Canada, India, and Norway). Lal (2003) also assessed the use of cover crops or meadow within a cropping rotation. The few studies he found on this management type again exhibited widely varying rates of C sequestration, from "minor" to 1.1 tons C $acre^{-1}$ yr^{-1} (Table 1).

Table 1. Summary of soil carbon sequestration rates found in the literature (December, 2006)

Management	C sequestration (tons C $acre^{-1}$ y^{-1})	Reference(s)	Number of studies or data points cited in reference*
Conversion of cropland to perennial grassland	0.07-0.54	Haynes et al. (1991); IPCC (1996); Mensah et al. (2003); Tyson et al. (1990)	NA
Adoption of conservation tillage	0.2 - 2.1	Lal (2003), citing Marland and West (2002) and Bayer et al. (2000); ISCC (2003)**; West and Post (2002)	2
Irrigation	0.05; 1.4	Conant et al. (2001); ISCC (2003)	2
Fertilization	0.13; 0.3	Conant et al. (2001); ISCC (2003)	42
Improved grazing	0.16; 0.2	Conant et al. (2001); ISCC (2003)	45
Introduction of legumes	0.33	Conant et al. (2001)	6
Introduction of earthworms	1.05	Conant et al. (2001)	2
Use of improved grass species	1.36	Conant et al. (2001)	5
Manuring or fertilization	0.03 – 2.0	Lal (2003), citing Ridley et al. (1990), Dersch and Bohm (2001), Malhi et al. (1997), Kundu et al. (2001), and Uhlen and Tveitnes (1995)	5
Rotation with meadows / cover crops	“minor” to 1.1	Lal (2003), citing Curtin et al. (2000) and Uhlen and Tveitnes (1995); ISCC (2003)	3

* for review articles (Conant et al. 2001; Lal 2003)
** ISCC (Idaho Soil Conservation Commission) values are expressed as MTCO2e, or million tons of CO_2 equivalents, which takes into account the radiative forcing of other GHGs, such as N_2O. The values from the ISCC report are listed separately unless they fall within the range of other values (only true for conservation tillage and cover crops).

Opportunities for Oregon Grass Seed Producers to Capture Carbon:

As stated earlier (Machado et al., 2006), grassland pastures are capable of sequestering greater amounts of carbon than conventionally tilled cropping systems (e.g., winter wheat systems), the amount varying as a function of climate, soil type, and historical land use (Scholefield, 2005). Perennial grass seed cropping systems, however, are not "grassland pastures," i.e., permanent pastures that exist for grazing livestock for extended periods. Grass seed contracts offered to growers by production companies for proprietary varieties are normally in the range of 2-3 years for perennial ryegrass and 3-5 years for tall fescue (*Festuca arundinacea* Schreb), fine fescue (*Festuca rubra),* orchardgrass (*Dactylis glomerata* L.) and bentgrass (*Agrostis* sp.). However, it is possible to find stands of older, publicly-grown varieties that have remained in production for longer periods, particularly orchardgrass and tall fescue.

Traditionally, grass seed producers have relied on extensive tillage prior to establishment of a perennial seed crop. This system has evolved as the best means available to remove all traces of the previously grown crop, and to prepare the fine, firm seedbed necessary to successfully sow small-seeded grasses. Once established, however, the cropping systems employ essentially no tillage operations. Historically, crop residues were removed by open-field burning, but this system as been much reduced for most grass species (e.g., perennial ryegrass, tall fescue, and orchardgrass). Today, baling the straw (for export) or full straw management is the approach used for most of the perennial ryegrass, tall fescue, and orchard grass seed crops.

Although there are no accurate data on the amount of straw returned to the field, we know that approximately 670,000 tons are baled and exported for feed use each year from the 485,000 acres of grass seed crops in the Willamette Valley. However, not all crop residue on those acres baled is removed. Estimates are that baled fields of tall fescue, perennial ryegrass and orchardgrass could contribute 1,750, 1,550, and 650 lbs per acre, respectively, crop residue to the soil. Given that there are currently 84,600 acres that contribute straw and stubble in tall fescue (out of 145,300 acres total), 146,700 acres that contribute straw and stubble in perennial ryegrass (out of 193,000 acres total), and 10,400 acres that contribute straw and stubble in orchardgrass (out of 17,300 acres total) this yields a total of 191,097 tons of residue from perennial seed crops. In addition, there are another 333,875 tons that are left on the fields (either managed as full straw or plowed out in rotation), for a total of 524,972 tons of residue. As open-field burning is still practiced on ~25,000 acres a year, one must subtract about 67,750 tons of straw residue available for C sequestration, yielding 457,222 tons of residue from perennial seed crops.

Annual ryegrass cropping systems (currently 125,000 acres) also contribute potential for C sequestration. In this system ~25,000 acres are still burned annually, but virtually none of the straw is baled for export. Of the 100,000 acres not burned, approximately 65-70% is flail chopped and plowed (followed by conventional tillage for seedbed preparation), 20-25% is no-tilled (through the full straw load and followed with a "sprout-spray" prior to emergence of the drilled crop), and 5-10% is managed as a "volunteer crop" (taking a subsequent crop from volunteer plants established from shattered seed germinating under the straw cover of the previous crop). If one assumes 2.75 tons of straw per acre, then annual ryegrass could contribute 275,000 tons of residue to the soil. However, this cropping system is not a "sustainable" long-term situation; growers will rotate between chopping and plowing and no-till or volunteer establishment every other or every third year, which likely has negative consequences for the long-term accumulation of carbon. Thus, it is difficult to estimate how much of this straw would contribute to C sequestration. For the purposes of this document we assume all could contribute to C sequestration, although this is likely an overestimate.

In summary, the sum of all major grass species grown for seed in western Oregon may yield approximately 732,222 tons of straw residue per year to the soil. Based on an average measured C content of 45% (John Hart, pers. comm.), this residue translates to 329,500 tons of C. However, microbial decomposition is not perfectly efficient. Roughly 70% of all C entering the soil system is lost as CO_2 (Brady and Weil 2002). Thus, the C actually sequestered is not likely to exceed 98,850 tons each year, assuming no change in microbial efficiency and no change in the amount of straw returned to the soil.

An alternative way to evaluate the potential for Oregon grass seed producers to sequester carbon is to compare the amount of C in soils that currently support grass seed fields to the amount of C in native soils of the same series. In the Willamette Valley, most grass seed fields are on Amity, Dayton, and Woodburn soils (John Hart, pers. comm.). Analysis of all available characterization data for those soils (Soil Survey Staff, 2007) indicated that the mean C content of native soils (those with no Ap horizon) was 4.94% ± 2.07% (n=10), whereas the mean C content for pedons of the same series with a plow layer (Ap horizon) was 2.08% ± 0.45% (n = 23). Thus, there is the potential for these soils to fix enough C to raise current C levels by roughly 3%, assuming moisture and nutrients (especially N) are non-limiting. This translates to roughly 27,000 lbs C per acre in the top 3 inches of soil, or 6,547,500 tons of C as an upper limit to the amount of additional C the 485,000 acres of soils currently supporting grass seed crops in the Willamette Valley could hold. Clearly, the capacity to store additional C far exceeds the amount of C returned to the soil via straw residue.

Uncertainties:

Although it is likely that grassland systems act as carbon sinks, much remains unknown about carbon cycling in soils and the long-term feasibility of managing soils for C sequestration. For example, soil C sequestration has a threshold capacity over a period of 50-100 years. Qian and Follet (2002) estimated that the "lifetime sink" capacity for the turfgrass systems they studied was 25-30 years. Thus, soil C sequestration is only a short-term solution. Once new practices or land use changes have been implemented, SOC sequestration will stabilize at a new equilibrium level of soil organic matter (IPCC 1996). Further, upon reaching SOC capacity, soil carbon must be maintained to successfully offset emissions. Any changes in land use (such as return to CT from NT) could release stored carbon back into the atmosphere, turning the soil into a net source rather than a sink for carbon.

In addition, there are potential feedbacks between atmospheric CO_2 concentrations and soil C storage. Sulzman et al. (2005) found that the addition of litter resulting from elevated atmospheric CO_2 could, rather than promoting greater storage of carbon in soils, cause a positive feedback to the atmospheric C pool by stimulating release of soil carbon. This process, known as priming, may reduce the effectiveness of soils for sequestering atmospheric carbon.

Similarly, there are feedbacks between climate and soil C storage. Leung and Ghan (1999) speculated that the Pacific Northwest will likely experience warming of 3.6ºF, a 50% reduction in snow, higher spring rainfall, and a slight increase in rainfall during other seasons over the next several decades. These potentially profound changes in climate are extremely likely to affect the potential of soils to sequester C. In a soil warming experiment in Alaska, Oechel et al. (1997) showed that increased temperatures, such as those expected in the future, could trigger large releases of soil C, especially in areas currently under permafrost.

With regard to grassland production systems, the lack of specific research regarding the impacts of intermittent tillage on SOC sequestration creates much uncertainty. Studies of soil C levels under intermittent tillage are critical to accurately estimate the carbon sequestration potential for grass seed producers in Oregon. The growing interest in no-till establishment for perennial grass seed crops might limit rotational use of conventional tillage as seed crops are taken out of production and new species or varieties are established. No-till establishment poses a significant challenge for small, shallow-seeded grass seed crops, but newer, precision-build drills are giving growers the means to develop methods that will save on the costs of conventional tillage. This also may provide an enhanced opportunity for the build-up of soil organic carbon.

Conclusion:

Increasing SOC storage through changes in land use and land management is a low cost and environmentally beneficial way of sequestering substantial amounts of atmospheric CO_2. Conversion of cropland to grassland, improved grassland management, and conversion to no-till farming can improve soil carbon sequestration. Although rates of sequestration and total SOC values vary among studies of grassland systems, it seems likely that grassland systems provide valuable carbon storage. To better understand the dynamics of carbon sequestration in grassland systems and to quantify the potential of Oregon grassland production systems to sequester carbon, further research, specifically targeted toward intermittent tillage, is necessary.

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Glossary

Abiotic— not associated with or derived from living organisms. Abiotic factors in an environment include sunlight, temperature, wind patterns, and precipitation

Actively cycling carbon: cycling of carbon in which carbon stays in a reservoir less than 1,000 years

Aggregation—the process whereby primary soil particles (sand, silt, clay) are bound together, usually by natural forces and substances derived from root exudates and microbial activity.

Anthropogenic—caused or produced by humans; induced or altered by the presence or activities of humans

Carbon cycle—the complex array of chemical, physical and biological processes by which carbon flows through the living and non-living environment

Carbon dioxide (CO_2)—a naturally occurring gas, also a by-product of burning fossil fuels and biomass, as well as land-use changes and other industrial processes. It is the principal anthropogenic →greenhouse gas that affects the earth's radiative balance

Conservation tillage (CT)—a tillage practice or system of practices that leaves plant residues on the soil surface for erosion control and moisture conservation.

Flow/Flux—the rate at which a variable enters or leaves a reservoir

Gigaton carbon (GT C)—amount of carbon equivalent to 10^9 metric tons carbon (1 metric ton equals 1,000 kilograms or 2,200 pounds)

Greenhouse effect—a warming effect in which certain atmospheric gases (greenhouse gases) allow short-wave solar radiation from the sun to enter the earth's atmosphere but capture a portion of the long-wave infrared heat emitted from the earth's surface, trapping heat in the atmosphere

Greenhouse gas—any of the gases whose absorption of solar radiation is responsible for the greenhouse effect, including carbon dioxide, methane, ozone, and the fluorocarbons

Mitigation—a human intervention to reduce the sources or enhance the sinks of greenhouse gases

No-till (NT)—planting crop seed directly into stubble or sod with no more soil disturbance than is necessary to get the seed into the soil

Pasture—lands composed of introduced or domesticated native forage species that are used primarily for the production of domestic livestock. They receive periodic renovation and/or cultural treatments, such as tillage, fertilization, mowing, and weed control. They are not in rotation with crops

Priming—stimulation of microbial activity in soil, usually organic matter decomposition, by the addition of labile organic matter

Productivity—the capacity of a soil or production system to produce a certain crop or other plants

Net primary production (NPP)—the accumulation of organic matter in plants, calculated as the difference between photosynthesis and respiration

Photosynthesis— the synthesis of complex organic materials, esp. carbohydrates, from carbon dioxide, water, and inorganic salts, using sunlight as the source of energy and with the aid of chlorophyll and associated pigments

Ppmv—parts per million by volume. A unit of measure often used in climate change terminology to express concentrations of atmospheric gases

Radiative forcing—a change in the balance between incoming solar radiation and outgoing infrared radiation. Without any Radiative forcing, solar radiation coming to the Earth would continue to be approximately equal to the infrared radiation emitted from the Earth

Respiration—the process in which an organism uses oxygen for its life processes and gives off carbon dioxide

Sink—a reservoir that takes up excess of a variable from a system; e.g., the ocean and soils are sinks for excess carbon dioxide

Soil organic carbon (SOC)—the carbon fraction of the soil that is organic (as compared to inorganic). This fraction generally contains organic acids, microbial bodies, etc., but does not contain dissolved inorganic carbon, such as carbonates.

Soil organic matter (SOM)—organic fraction of the soil; includes plant and animal residues at various stages of decomposition, cells and tissue of soil organisms, and substances synthesized by the soil population

Source—a reservoir that supplies a variable to a system; e.g., fossil fuels are a source of carbon dioxide to the actively cycling carbon pool

Tillage—the turning over of a soil in agricultural fields